Results from FOPI on nuclear collective flow in heavy ion collisions at SIS energies

N. Bastid

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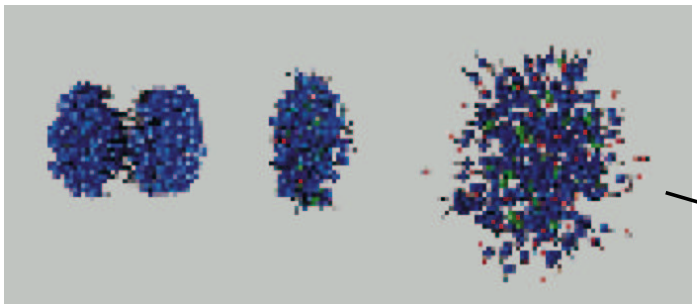
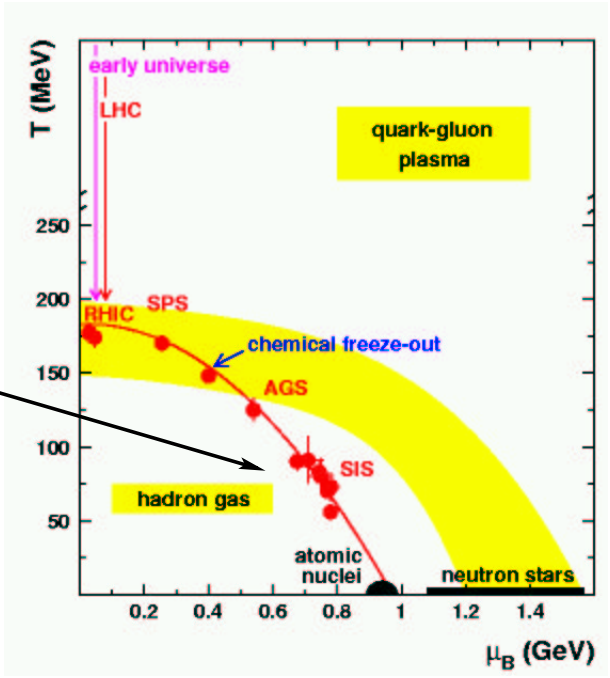




1 Motivations

2 FOPI detector overview

3 Experimental systematics

- Directed flow
- Elliptic flow

4 Data *versus* IQMD

- Sensitivity to σ_{nn}?
- Sensitivity to EoS?

5 Anisotropic flow from Lee-Yang Zeroes

6 Conclusion

Ca + Ca, Ni + Ni, Ru + Ru, Xe + CsI, Au + Au

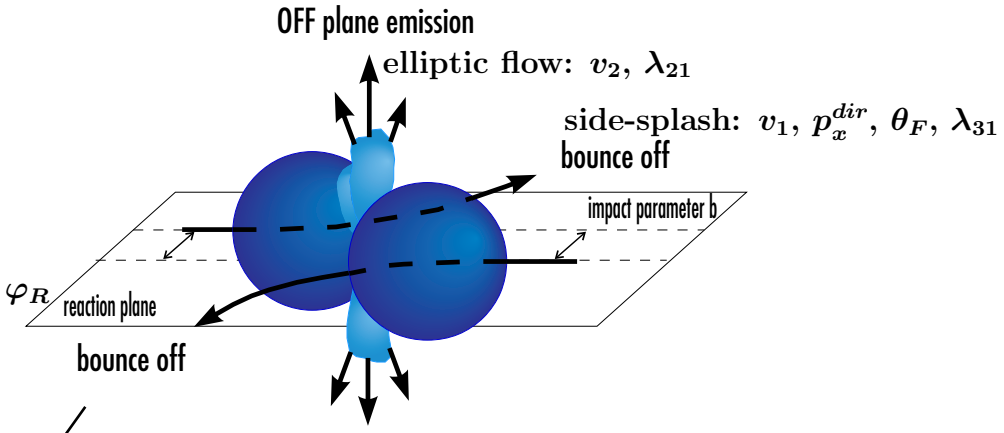
90A MeV - 2A GeV

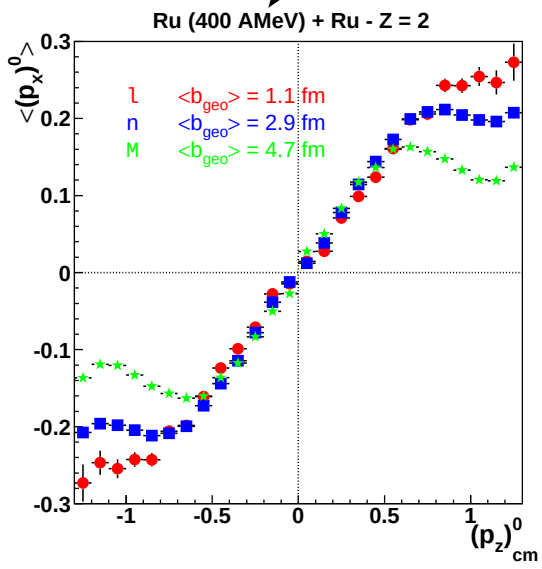
Motivations & Observables

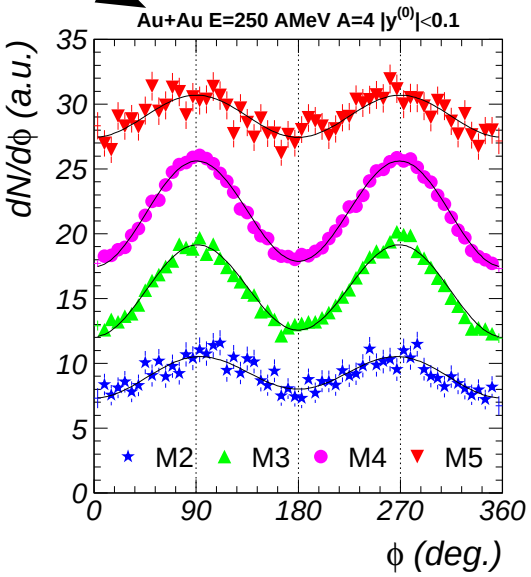
Probing hot & dense hadronic matter

↪ Nuclear Equation of State

- ☐ Collision dynamics
- ☐ In-medium effects: σ_{nn}, MDI





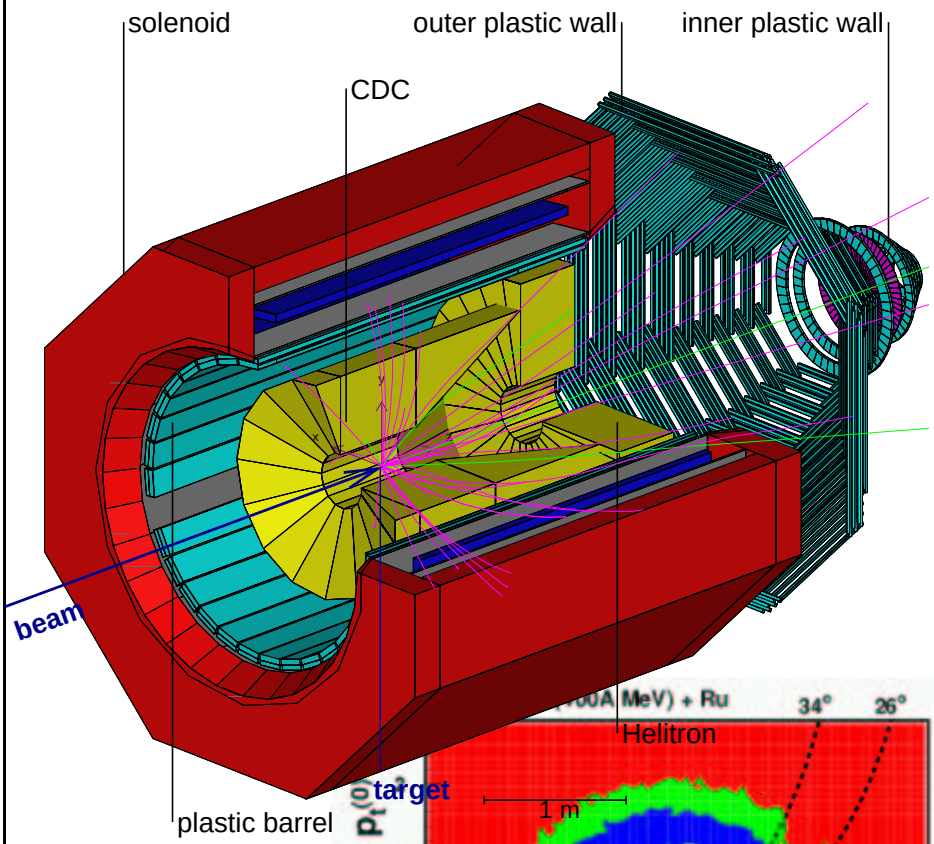


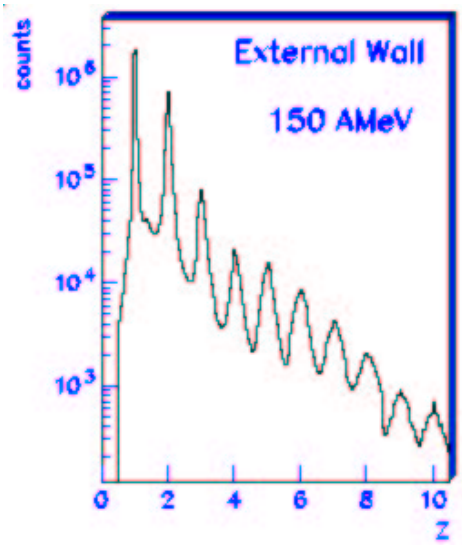
Global flow : $p_x^{dir} = \sum \mathrm{sign}(y_{cm}) Z u_x \Big/ \sum Z, \quad u_x = \beta_x \gamma$

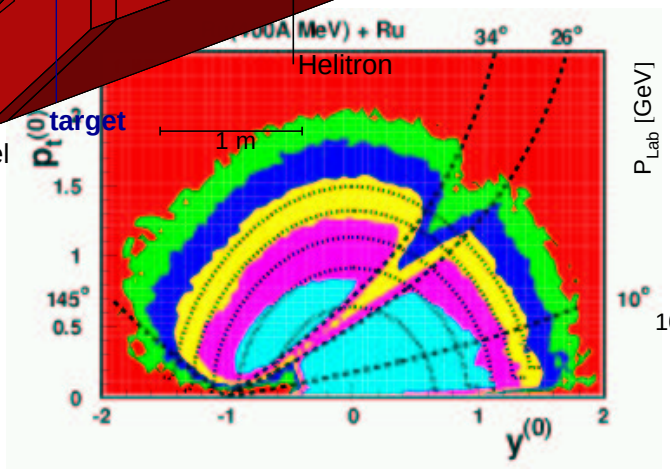
Flow angle: θ_F, Aspect ratios: λ_{31} & λ_{21}

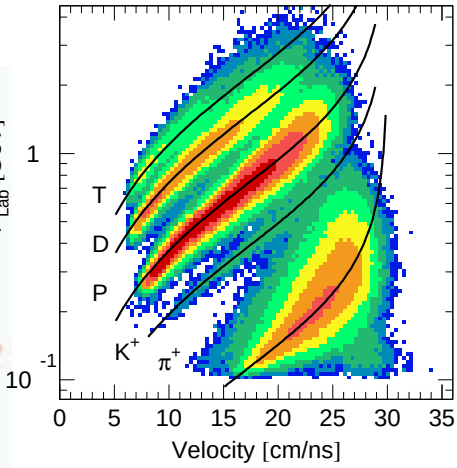
Differential flow : $\dfrac{dN}{d\varphi'} \sim 1 + 2v_1 \cos(\varphi') + 2v_2 \cos(2\varphi'), \quad \varphi' = \varphi - \varphi_R$

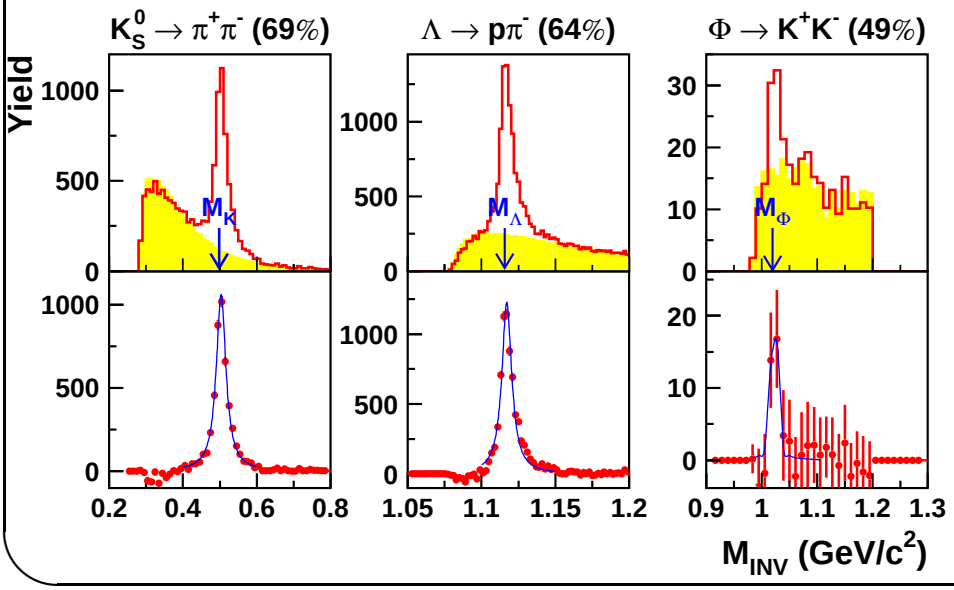
FOPI detector @ GSI

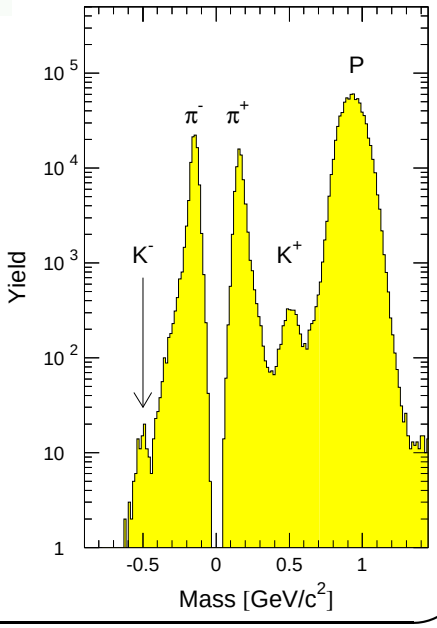




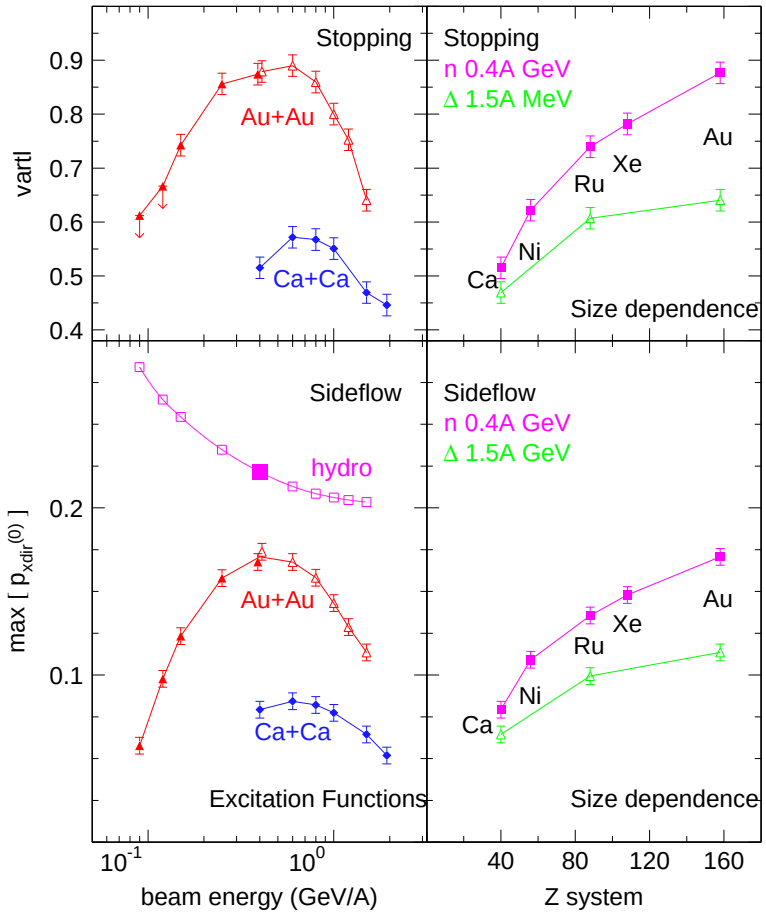








Systematics of Directed Flow & Stopping



W. Reisdorf et al., (FOPI), PRL 92 (2004) 232301

Stopping:

$b/b_{max} < 0.15$

$\mathrm{vartl} = \dfrac{\sigma^2(y_t)}{\sigma^2(y_z)}$

Sideflow:

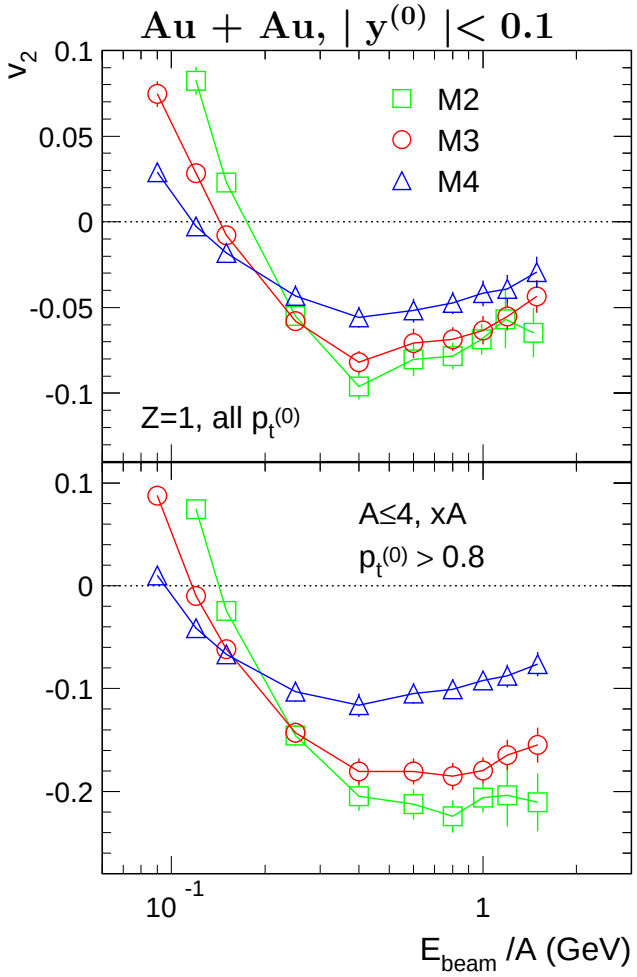
$b/b_{max} \simeq 0.3$ - 0.4

$\mathrm{max}\ [(p_x^{dir})^{(0)}]$

- Correlation between stopping & flow & pressure
- Evidence for incomplete stopping

- **Stopping:** maximum $\sim$ 400A MeV
  decreasing towards higher beam energies
  rising with system size, no saturation
  below expectations from hydrodynamics

Systematics of Elliptic Flow



- Transition from in-plane to out-of-plane preferred emission at low energies
- Maximum $\sim$ 400A MeV (depending on Pt)
- v_2 decreasing toward higher beam energies

A. Andronic et al., (FOPI), GSI Report 2004-1 (2004) 54

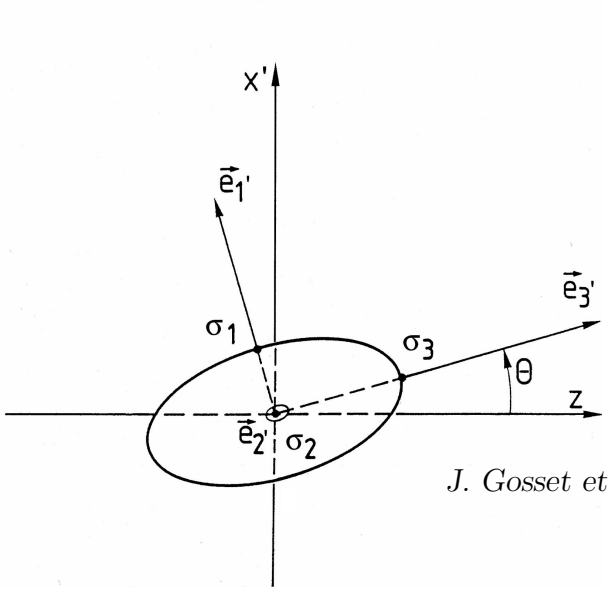
- Interplay between fireball expansion & spectator shadowing
- Passing time decreasing at high beam energies

- Influence of collision dynamics
- Information on different stages of the collision

$\Rightarrow$ High p_t particles messengers of high density phase

T. Gaitanos et al., Eur. Phys. J. A 12 (2001) 421

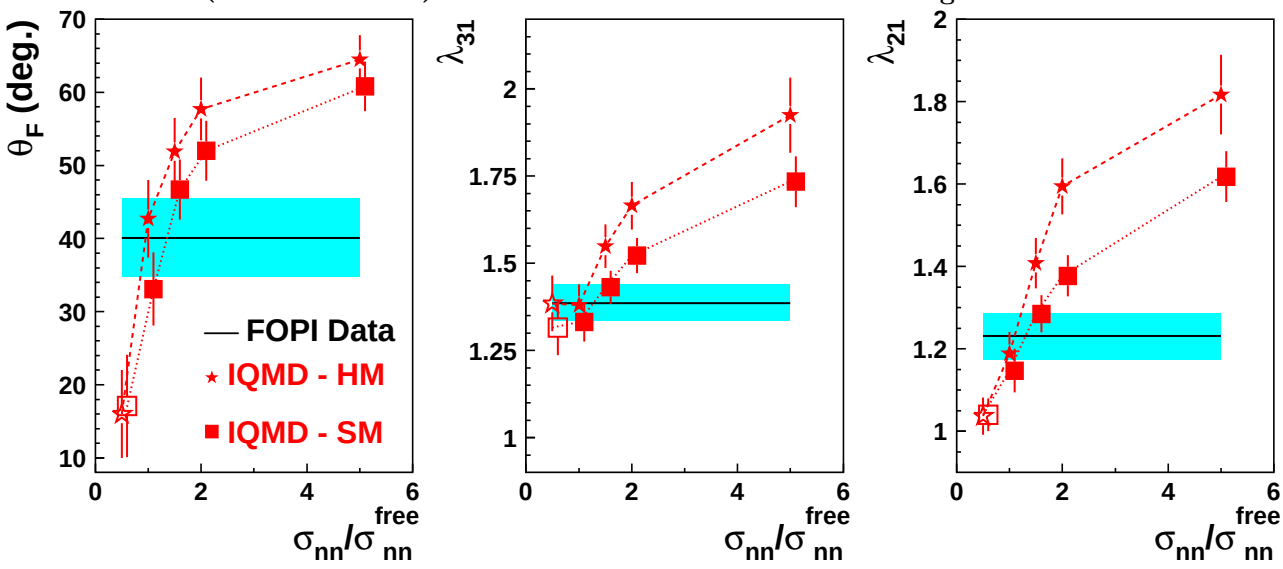
Shape parameters: Sensitivity to in-medium σ_{nn}?



- $\theta_F \rightarrow$ Directed flow
- $\lambda_{31} = f_3^2/f_1^2 \rightarrow$ Directed flow & Stopping
- $\lambda_{21} = f_2^2/f_1^2 \rightarrow$ Elliptic flow

J. Gosset et al., (DIOGENE), Phys. Lett. B 247 (1990) 233

Ru (400 AMeV) + Ru - Proton-likes - $< b_{geo} > = 1.1$ fm



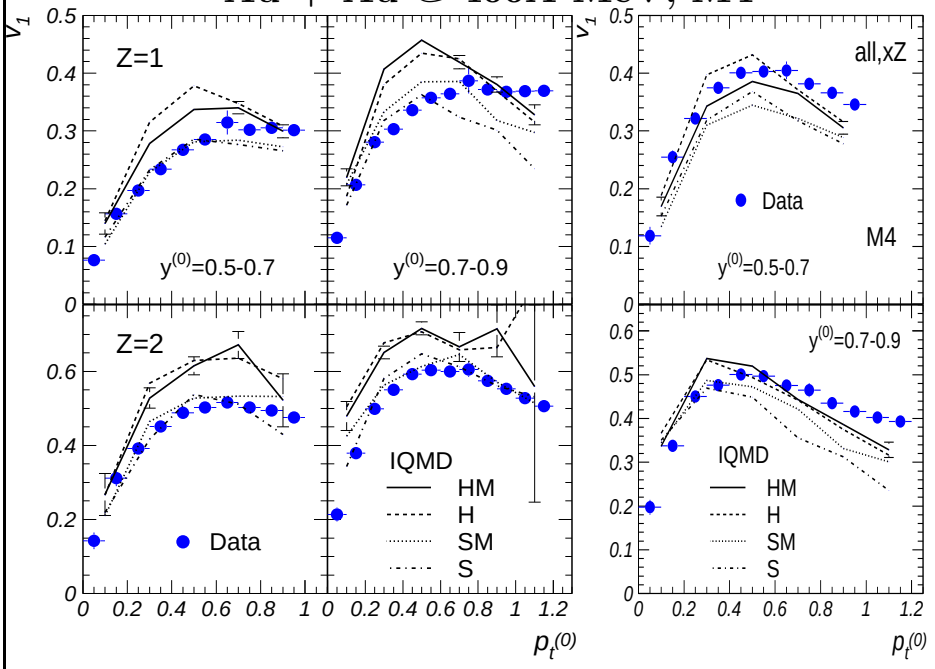
N. Bastid et al., (FOPI), Nucl. Phys. A (2004), in press

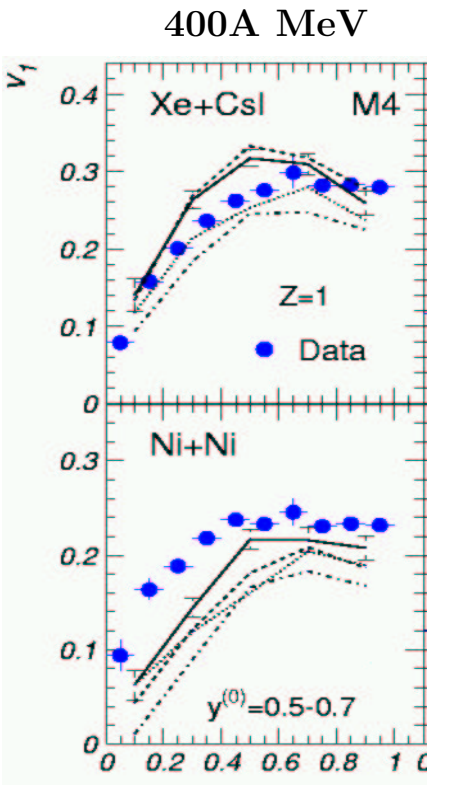
Data favour in-medium σ_{nn} close or slightly higher than σ_{nn}^{free}

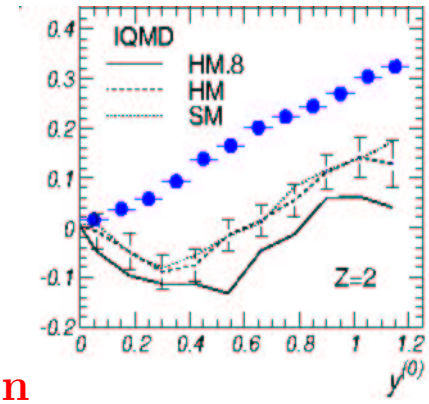
$\Rightarrow$ Consistent with results on nuclear stopping

F. Rami et al., (FOPI), Phys. Rev. Lett. 84 (2000) 1120
B. Hong et al., (FOPI), Phys. Rev C 66 (2002) 034901

EoS from Directed Flow?



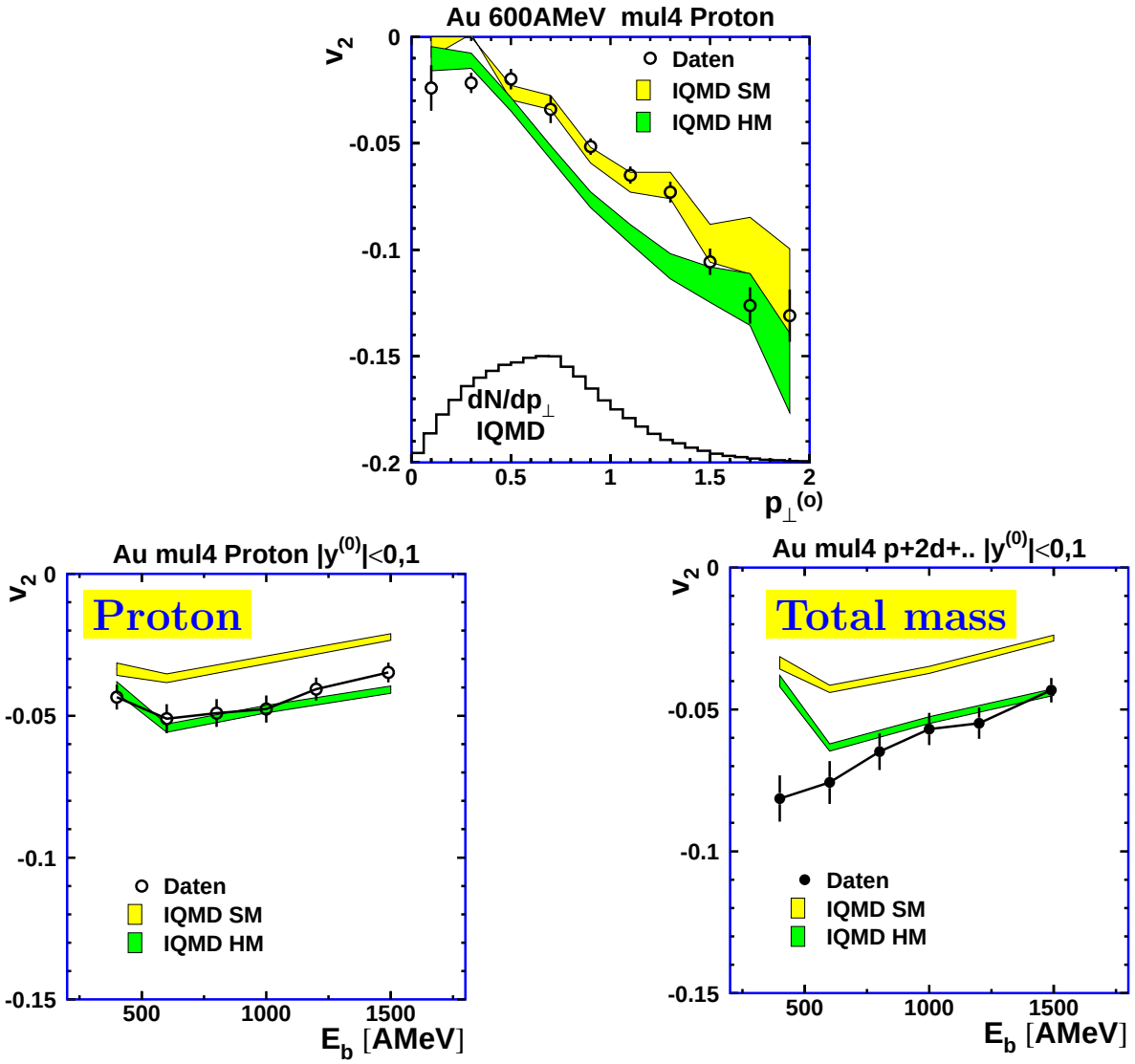




A. Andronic et al., (FOPI), Phys. Rev C 67 (2003) 034907

- **Sensitivity to the EoS parametrization**
- **Soft EoS (with MDI & σ_{nn}^{free}) in best agreement with directed flow data for Au + Au & Xe + CsI at 400 AMeV**
- **Difficulties of the model to reproduce directed flow *versus* system size & low E_{beam} (90A MeV)**

EoS from Elliptic Flow?



T. Kress, (FOPI), PhD, Darmstadt (2002)

- **Proton elliptic flow in qualitative agreement with IQMD**
- **Light fragments & IMF (Z>2) abundantly produced at SIS energies**
- **Bound protons/all protons:**

  $\hookrightarrow$ 67% (400A MeV) $\rightarrow$ 33% (1500A MeV)

$\Rightarrow$ Total baryon elliptic flow not described by any EoS

Flow from Lee-Yang Zeroes method

Genuine flow directly from correlation between many particles

⇒ Non-flow correlations due to quantum statistics, resonance decays, momentum conservation effects, ..., not neglected

□ **Generating function:**

$$G(ir) = \left\langle \prod_j \left[1 + ir\omega_j \cos(n(\varphi_j - \theta))\right] \right\rangle_{events}$$

$$\text{where } \ln G(ir) = \sum_{k=1}^{+\infty} c_k \frac{(ir)^k}{k!},\ c_k = \text{cumulant}$$

□ **Find first zeroe (minimum), r_0^θ, of $|\ G(ir)\ |$**

$r_0^\theta \rightarrow$ Asymptotic behaviour of c_k in the expansion of $\ln G(ir)$

□ **"Integrated" flow:** $V_n^\theta\{\infty\} = \dfrac{j_{01}}{r_0^\theta}$ (& averaged over θ)

□ **Resolution parameter:** $\chi = \dfrac{V_n\{\infty\}}{\sigma}$

→ $\chi > 1$: Lee-Yang zeroes should be used

→ $0.5 < \chi < 1$: Important to optimize weights

→ $\chi < 0.5$: Large statistical errors, better to use cumulants

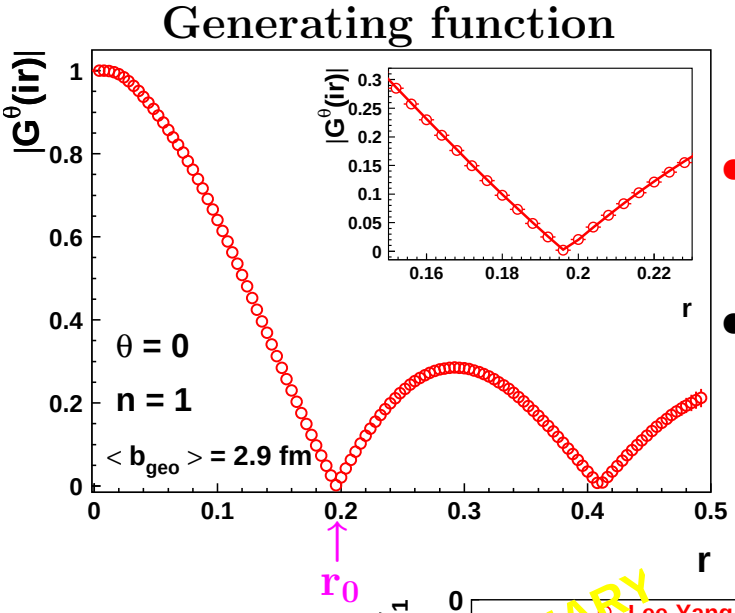
□ **Differential flow:**

→ Deduced from $V_n^\theta\{\infty\}$ in harmonics multiples of n

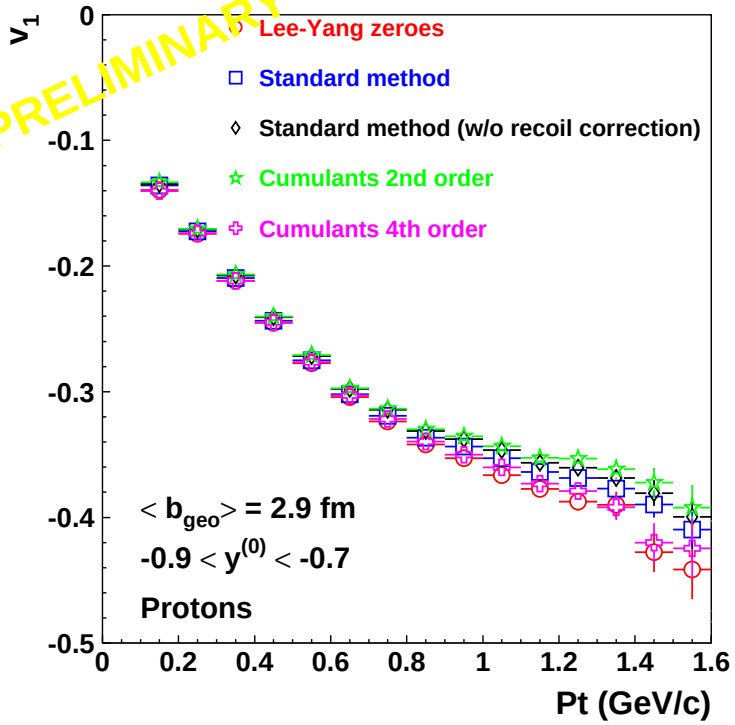
Detailed description in:

R.S. Bhalerao et al., Phys. Lett. B 580 (2004) 157 & *Nucl. Phys. A 727 (2003) 373; N. Borghini et al., nucl-th/0402053 (2004*

First application of Lee-Yang theory to FOPI data: Ru + Ru @ 1.69A GeV



- $\chi = 1.45 \Rightarrow$ Lee-Yang Zeroes theory can be used
- Clear indication of collective effects



- Non-flow effects from 4-particle correlations negligible
- Evidence for (small) momentum conservation effects on v_1
- Non-flow effects negligible for higher harmonics

Ongoing development $\rightarrow$ $\pi^{\pm}$ flow & influence of Δ decay?

(110 Millions central Ni + Ni @ 1.93A GeV)

Conclusion

Complete set of data at SIS energies measured with FOPI:

- Variation of beam energy from 90A MeV to 2A GeV
- Variation of system size from Ca to Au
- Variation of asymmetry in isospin (Ru/Zr)
- Variation of asymmetry in system size (Au/Ca & Pb/Ni)

- Main dependences of directed & elliptic flow are available

- New procedure of Lee-Yang Zeroes (& cumulants at SIS) successfully used for first time to analyze flow
- Correlations from non-flow effects negligible for protons & composite particles

- Most features of flow data reproduced qualitatively well by IQMD model but not in detail

- EoS is influencing different observables
- EoS is linked to in-medium NN interaction

  $\Rightarrow$ momentum dependence, cross sections
- Non-equilibrium effects important

FOPI Collaboration

A. Andronic, V. Barret, Z. Basrak, N. Bastid,
M.L. Benabderrahmane, R. Čaplar, E. Cordier, P. Crochet, P. Dupieux,
M. Dželalija, Z. Fodor, I. Gasparić, Y. Grishkin, O. Hartmann, N. Herrmann,
K.D. Hildenbrand, B. Hong, D. Kang, J. Kecskemeti, Y.J. Kim,
M. Kirejczyk, P. Koczon, M. Korolija, R. Kotte, M. Kowalczyk, T. Kress,
A. Lebedev, Y. Leifels, X. Lopez, A. Mangiarotti, V. Manko, T. Matulewicz,
M. Merschmeyer, D. Moisa, D. Pelte, M. Petrovici, F. Rami, W. Reisdorf,
A. Schuettauf, Z. Seres, B. Sikora, K.S. Sim, V. Simion,
K. Siwek-Wilczyńska, M. Smolarkiewicz, V. Smolyankin,
J. Soliwoda-Poddany, M. Stockmeier, G. Stoicea, Z. Tyminski,
K. Wiśniewski, D. Wohlfarth, Z. Xiao, I. Yushmanov, A. Zhilin

NIPNE Bucharest, Romania
KFKI Budapest, Hungary
LPC Clermont-Ferrand, France
GSI Darmstadt, Germany
Univ. of Heidelberg, Germany
IKH Rossendorf/Dresden, Germany
ITEP Moscow, Russia
Kurchatov Institute, Moscow, Russia
Korea University Seoul, Korea
IReS Strasbourg, France
RBI Zagreb, Croatia
Univ. of Warsaw, Poland

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